

Energy from waste: carbon footprint of incineration and landfill biogas in the UK

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Abstract

Purpose The majority of waste in many countries is still landfilled. This represents waste of valuable resources and could lead to higher emissions of greenhouse gases (GHG) compared to energy recovered by incineration, even when the landfill gas is recovered. This paper aims to find out which option is more sustainable with respect to the carbon footprint (global warming potential) by comparing energy recovered from MSW incineration with that from biogas recovered from landfilled waste.

Materials and methods Life cycle assessment has been used as a tool, following the ISO 14040/44 and PAS 2050 methodologies. Data have been sourced from the operator of the incinerator, the Environment Agency for England and Wales, the CCaLC and Ecoinvent databases. CCaLC v2 and GaBi v4.3 have been used for the LCA modelling.

Results and discussion The carbon footprint of MSW incineration is $-0.179 \text{ t CO}_2 \text{ eq./t MSW}$ while that from landfilling is $0.395 \text{ t CO}_2 \text{ eq./t MSW}$, with both systems credited for energy recovery. The results are sensitive to the composition of waste, energy options chosen to credit the systems and the recovery rate of biogas. Increasing the amount of fossil carbon in the waste by increasing paper recycling between 40 and 80 % increases the carbon footprint of incineration by 9–20 %. If instead of the electricity from the UK grid, electricity from heavy fuel oil or coal is

assumed to be displaced by incineration, its carbon footprint reduces to -0.51 and $-0.35 \text{ t CO}_2 \text{ eq./t MSW}$, respectively. Increasing the landfill gas recovery from 53 to 75 % and its utilisation for energy from 35 to 50 %, reduces the carbon footprint of landfilling by a half.

Conclusions The results indicate that waste incineration offers significant savings of GHG compared to disposal by landfill. Based on the total amount of MSW of 225,000 t/year considered in this study, MSW incineration could save around 129 kt of CO_2 eq. per year compared to landfilling with biogas recovery, with both systems co-generating heat and electricity. At the UK level, diverting all MSW that is currently landfilled to incineration with energy recovery could save around 8.38 million tonnes of CO_2 eq. per year or 1.5 % of the total UK GHG emissions. These savings can be increased further by recycling of bottom ash and non-ferrous metals. Incineration remains a better option than landfilling under all the conditions considered in this study.

Keywords Carbon footprint · Energy · Incineration · Landfill biogas · Life cycle assessment · Municipal solid waste

1 Introduction

Municipal solid waste (MSW) management is an important and challenging issue for sustainable development. It is also one of the most controversial topics and the subject of an ongoing debate between different stakeholders. A particularly ‘difficult’ issue is MSW incineration which has in many countries become a socially unacceptable option for dealing with solid waste owing to health, transport, aesthetic and other concerns (see e.g. Ares and Bolton 2002; Azapagic 2011). On the other hand, the increasing amounts

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of waste require timely and practical solutions to the problem which currently cannot be solved by recycling alone.

Around 3 billion tonnes of MSW are generated in Europe annually (EC 2010). As shown in Fig. 1, despite the increasing recycling rates, in many European countries the majority of MSW is still landfilled (EC 2008). Only a small proportion of MSW is incinerated to recover energy, generating 4 % of European renewable electricity and 41 % of renewable heat (IEA 2011). Carbon emissions from waste account for 3 % of the EU's total carbon footprint, the vast majority of which comes from landfills (EC 2011).

In the UK, half of the waste generated in 2008/2009 was disposed of by landfill (Defra 2007, 2009). This has decreased to 43 % in 2010/2011 owing to legislation such as the EU Landfill Directive (EC 1999) and landfill tax (Defra 2010). The waste diverted from landfill is mainly recycled and some is incinerated. The latter increased in the UK from 9 % in 2000/2001 to 20 % in 2010/2011, of which 15 % was incineration with energy recovery (Defra 2011).

Landfilling of MSW represents waste of valuable resources and could lead to higher emissions of greenhouse gases (GHG) compared to incineration with energy recovery, even when the landfill biogas is captured and utilised. This paper aims to find out how the two options compare on a life cycle basis with respect to their carbon footprints. The study is based in the UK and compares incineration of MSW in a state-of-the-art combined heat and power plant (CHP) with recovery and utilisation of landfill biogas for heat and electricity co-generation. Life cycle assessment (LCA) has been used as a tool for these purposes following the ISO 14044 (ISO 2006) and PAS 2050 (BSI 2011) methodologies.

A number of other studies have also used LCA to estimate the carbon footprint of waste incineration and/or landfill (e.g.

Arena et al. 2003; Consonni et al. 2005; Eriksson et al. 2005; Finnveden et al. 2005; Azapagic 2007; Liamsanguan and Gheewala 2007; Morselli et al. 2008; Riber et al. 2008; Astrup et al. 2009; Cherubini et al. 2009; Papageorgiou et al. 2009; Rigamonti et al. 2009; Fruergaard and Astrup 2011). However, only three studies have been found in the literature that considered incineration in a CHP plant, two of which are based in Italy (Consonni et al. 2005; Rigamonti et al. 2009) and one in the UK (Papageorgiou et al. 2009); the latter did not consider landfill biogas utilisation. Therefore, as far as the authors are aware, this is the first study of its kind for the UK.

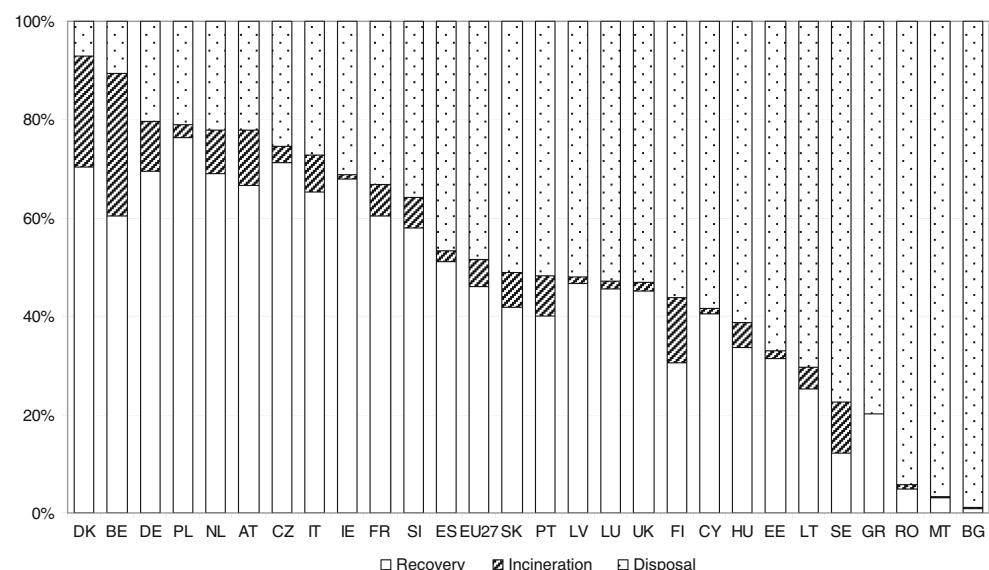
2 Methodology

2.1 Goal and scope of the study

The goal of this study is to estimate and compare the carbon footprints of MSW disposal by incineration and by landfill, with both options recovering energy. The functional unit is defined as 'disposal of 1 tonne of MSW'. The system boundary includes the following life cycle stages:

- Incineration: transport and incineration of waste; construction of the incinerator; generation of heat and electricity and associated energy credits; flue gas treatment and associated inputs, outputs and infrastructure; transport and landfilling of ash and air pollution control residue; and recycling of ferrous metals.
- Landfilling: transport of waste to landfill; landfill construction, operation and aftercare; recovery of biogas; generation of heat and electricity and associated energy credits; and water effluent (leachate) management.

Fig. 1 Waste management in Europe (EC 2008) [latest data available at the time of writing]



2.1.1 Incineration

The MSW incinerator considered is a state-of-the-art combined heat and power incinerator with moving grate typically found in the UK and elsewhere in Europe. With a capacity of 225,000 tonnes of MSW per year, it can co-generate up to 19 MW of (net) electricity and 60 MW of heat (Veolia 2008). This translates to an average of 1,550 MJ of electricity and 1,740 MJ of heat per tonne of MSW with an average heating value of 9,200 kJ/kg.

The life cycle of the incineration system is shown in Fig. 2 and the plant layout in Fig. 3. The waste is collected and transported for 45 km to the plant where it is stored in a bunker before being transferred to the incineration chamber. The waste is combusted at temperatures >850 °C; natural gas is used for the initial start-up and to maintain the high combustion temperatures (Table 1). To control the emissions of NO_x, acid gases and dioxins, urea, hydrated lime and activated carbon are injected into the flue gas (see Table 1); particulates are removed in filter bags. The air emissions are given in Table 2. Around 65 % of the air pollution control residue is recycled within the plant to increase the efficiency of emissions control, while the rest (28 kg/t) is landfilled together with the bottom ash (220 kg/t). A transport distance to the landfill of 45 km has been assumed. Ferrous metals are recovered from the bottom ash and recycled locally.

Typical MSW composition (Table 3) in the UK is assumed in the study and has been used as a basis for estimating the stack emissions of carbon dioxide (CO₂) from incineration, as follows (IPCC 2006):

$$E_{\text{CO}_2} = \text{MSW} \times \sum (\text{WF}_j \times \text{DM}_j \times \text{CF}_j \times \text{FCF}_j \times \text{OF}_j) \times 44/12(\text{t}) \quad (1)$$

where:

E_{CO_2} CO₂ emissions from MSW combustion (t)
MSW Amount of municipal solid waste (as wet weight) (t)

WF _j	Fraction of waste component <i>j</i> in the MSW (as wet weight)
DM _j	Fraction of dry matter content in the component <i>j</i> of the MSW
CF _j	Fraction of carbon in the dry matter of component <i>j</i>
FCF _j	Fraction of fossil carbon in the total carbon of component <i>j</i>
OF _j	Oxidation factor (assumed equal to 1)
44/12	Conversion from C to CO ₂

2.1.2 Landfilling

In the UK and in the EU, MSW is disposed of in managed ('sanitary') landfills with recovery of biogas and a leachate collection system. Therefore, such a landfill is considered in this study. The life cycle of the system is shown in Fig. 4. As for the case of incineration, the same composition of waste (see Table 3) and transport distance to the landfill (45 km) are assumed.

To estimate the amount of biogas produced based on the MSW composition as well as the related carbon emissions, the methodology proposed by Doka (2009) and the Ecoinvent tool for modelling MSW sanitary landfills (Ecoinvent 2008) have been used. As a result, it is estimated that the landfill would generate 1,363 MJ of biogas per tonne of MSW. Following the assumptions in Doka (2009), 47 % of landfill gas (640 MJ/t MSW) is assumed to be vented to the atmosphere. The remaining 53 % is recovered as follows: 18 % (245 MJ/t MSW) is flared and 35 % (477 MJ/t MSW) is utilised for energy generation. To make the landfill biogas system comparable to incineration, co-generation of heat and electricity in a CHP is assumed. However, this is not the current practice in the UK where landfill biogas is typically used for electricity generation (EA 2004); the latter is considered as part of the sensitivity analysis in Section 3.3. The assumed net generation of electricity per megajoule of

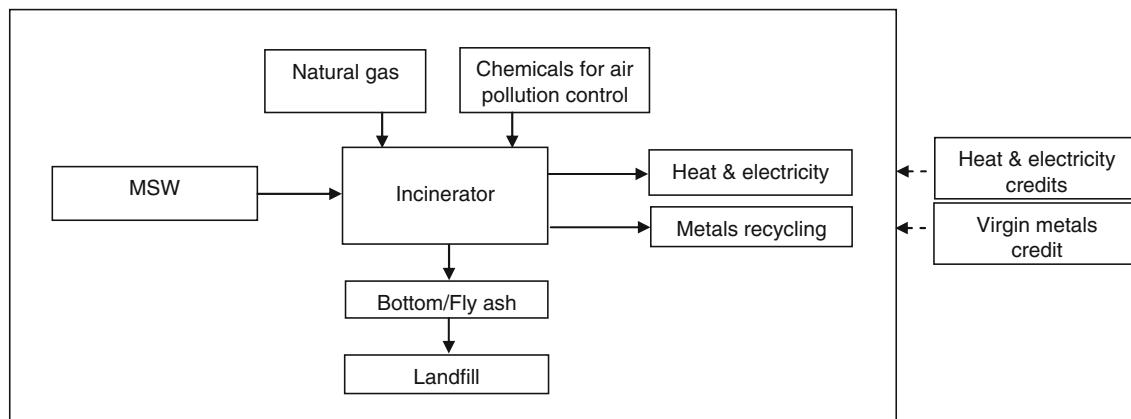


Fig. 2 Life cycle flow diagram of the waste incineration system

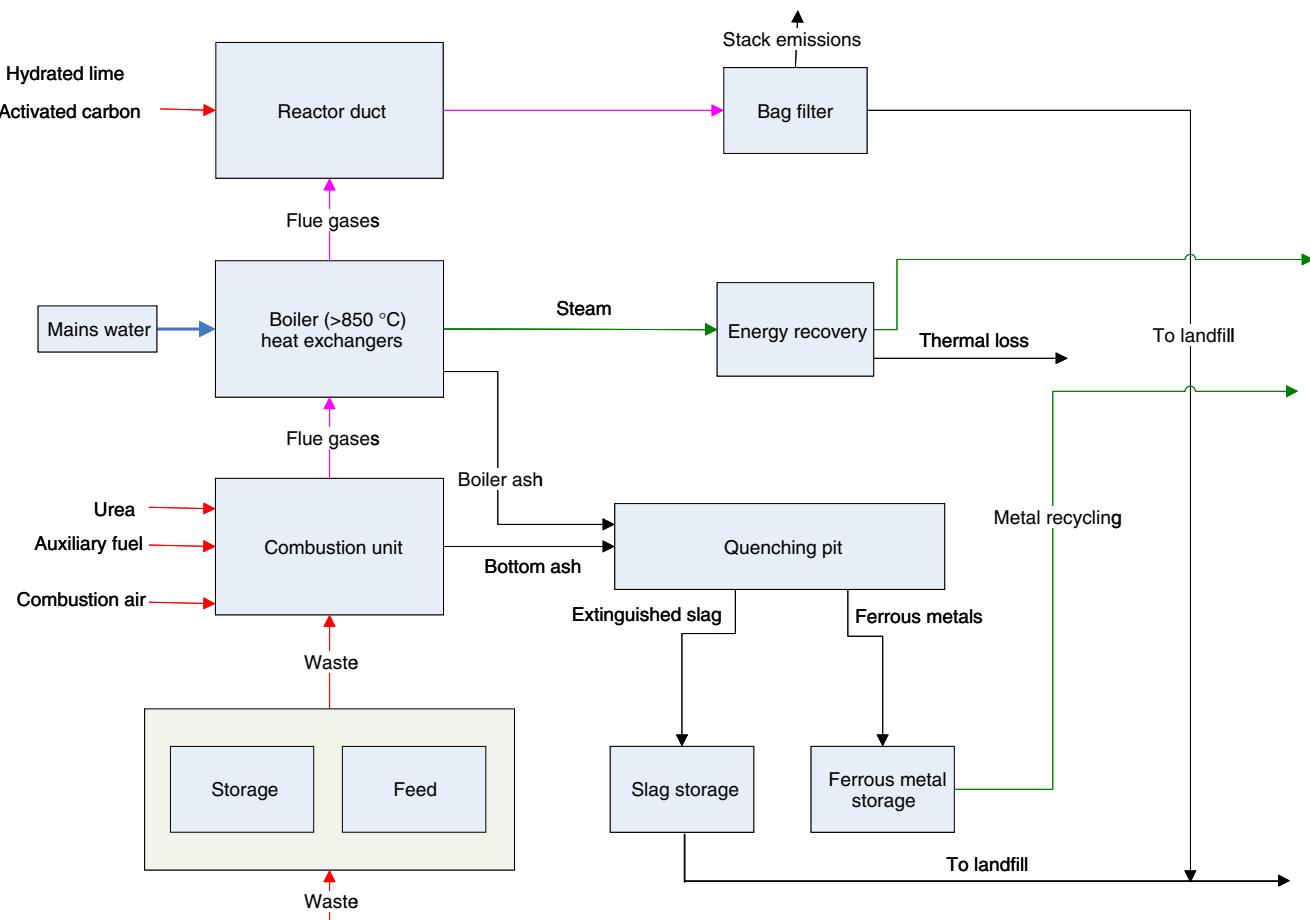


Fig. 3 Flow diagram of the incinerator (based on data from EA 2010)

the recovered biogas is 0.278 MJ and of heat is 0.135 MJ (Doka 2009). Therefore, based on this assumption of electricity-to-heat ratio, 477 MJ per tonne of MSW of utilised biogas will generate 133 MJ of electricity and 64 MJ of heat per tonne MSW. The leachate emissions from the landfill are estimated at 2,500 l per tonne of MSW (Doka 2009). It is also assumed that 46.7 MJ of diesel per tonne of MSW is required for the operation of landfill machinery and 4.86 MJ/t of electricity for landfill gas pumps (Doka 2009).

Table 1 Consumables used in the incinerator (EA 2010)

Consumable	Amount (per tonne of MSW)
Hydrated lime [kg]	11.6
Activated carbon [kg]	0.4
Urea [kg]	1.5
Auxiliary fuel (natural gas) [MJ]	278
Mains water (for steam generation and ash quenching) [l]	129

2.2 Data sources

The data for the operation of the incineration system are based on the CHP incinerator in Sheffield and have been obtained from the operator (Veolia 2008) and the Environment Agency for England and Wales (EA 2010). The life cycle data for the rest of the incineration system and for the landfill system have been sourced from the CCaLC (2011) and Ecoinvent databases (Ecoinvent 2007). The data for the landfill biogas system have been also sourced from these databases as well as from the Environment Agency for England and Wales (EA 2004). As mentioned in the previous section, the Ecoinvent tool for MSW landfilling (Ecoinvent 2008) has been used to model the carbon emissions from the biogas system.

2.3 System credits

Both systems have been credited for the outputs that they generate: in the case of incineration, for the heat, electricity and recycling of ferrous metals; and in the case of landfill, for electricity and heat generation from the recovered biogas (see Figs. 2 and 4). System expansion has been used for

Table 2 Air emissions from the incinerator (Veolia 2008; EA 2010)

Pollutant	Emission (kg/t MSW)
CO ₂ ^a	216
CO	0.02
SO ₂	0.08
NO _x	0.7
N ₂ O	0.31
HCl	0.04
NH ₃	0.006
HF	0.0003
PM ₁₀	0.004
Dioxins/furans	3.62×10 ⁻¹¹

^aEstimated using waste composition in Table 3 and Eq. 1

these purposes, following the ISO 14044 and PAS 2050 standards (ISO 2006; BSI 2011). The incineration system has been credited for displacing heat from natural gas, electricity from the UK grid and production of virgin ferrous metals. Overall, the credit amounts to 0.47 tonnes of CO₂ eq. per tonne of MSW (Fig. 5) from the recovery of 1,550 MJ of electricity, 1,740 MJ of heat and 23 kg of ferrous metals per tonne of waste. The landfill system has been credited for 0.029 tonnes of CO₂ eq. per tonne of MSW for the recovery of biogas and the associated generation of 133 MJ of electricity and 64 MJ of heat (Fig. 6). The figures for the carbon credits have been obtained from the Ecoinvent database (Ecoinvent 2007).

3 Results and discussion

3.1 Carbon footprint of energy from incineration vs landfill biogas

CCaLC (2011) and GaBi software (PE 2007) have been used to model the incineration and landfilling systems and

to estimate their carbon footprints; the results are presented in Fig. 6. As shown, if incineration is not credited for the generation of heat, electricity and ferrous metals recycling, the total carbon footprint is 0.290 t CO₂ eq./t MSW. With the credit, this value reduces to −0.179 t CO₂ eq./t MSW, which means that incineration saves 0.469 t CO₂ eq./t MSW.

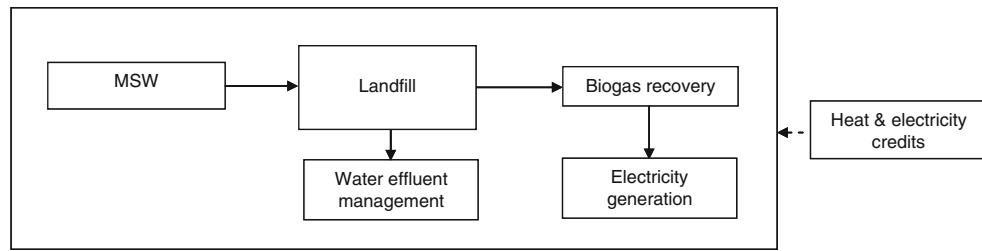
The results agree well with other studies which report the carbon footprint of CHP incinerators in the range from −0.13 to −0.23 t CO₂ eq./t MSW (Fig. 7). This is despite the differences in the technologies, scales, composition of waste and different geographical regions covered by the studies. For example, Consonni and the collaborators considered a 600-kt MSW/year incinerator in Italy, assuming in one case (“Cog A”) cogeneration of 699 kWh of electricity/t MSW and 2,287 MJ/t of heat and in another (“Cog B”) 587 kWh of electricity and 4,574 MJ of heat (Consonni et al. 2005). The estimated carbon footprints were −0.134 and −0.212 t CO₂ eq./t MSW for “Cog A” and “Cog B”, respectively (see Fig. 7), assuming 19 % of plastics in the waste and the credits for displacing a conventional steam power plant firing 50 % natural gas and 50 % heavy oil. Rigamonti et al. (2009) studied a large- and a small-scale incinerator also in Italy, estimating the carbon footprints at −0.231 and −0.182 t CO₂ eq./t MSW, respectively (see Fig. 7). The system was credited for heat from natural gas and electricity from the Italian grid. However, it is not clear what the composition of the waste was or how much electricity and steam was produced. Finally, the study by Papageorgiou et al. (2009) of a CHP incinerator in England found that if the system is credited for natural gas and electricity from the UK grid, the carbon footprint is equal to −0.148 t CO₂ eq./t MSW. The waste composition is similar to that considered in this study but the size and the energy output from the incinerator are not specified.

The GHG savings from incineration could be increased further if the bottom ash is diverted away from landfill and utilised in construction (as aggregate) and if other materials

Table 3 Composition of MSW

MSW component	MSW composition (DF) (% of wet weight) (adapted from Parfitt 2002)	Fraction of dry matter (DM) [IPCC 2006]	Total carbon fraction (CF) in dry weight [IPCC 2006]	Fossil carbon fraction (FCF) in total carbon [IPCC 2006]
Card/paper	18	0.90	0.46	0.01
Nappies	2	0.40	0.70	1.00
Garden waste	23	0.40	0.49	0
Kitchen waste	17	0.40	0.38	0
Glass	7	1.00	0.00	0
Wood/furniture	5	0.85	0.50	0
Scrap metal	8	1.00	0.00	0
Plastic	7	1.00	0.75	1.00
Textiles	3	0.80	0.50	0.20
Other	10	0.90	0.03	1.00

Fig. 4 Life cycle flow diagram of the landfill biogas system



such as carbon and non-ferrous metal are also recovered. These have not been considered in this study as they are currently not widely implemented in the UK.

By comparison, the carbon footprint of landfilling with and without the credit for the biogas recovery is equal to 0.395 and 0.423 t CO₂ eq./t MSW, respectively (see Fig. 6). As indicated in Fig. 8, these results compare well with other studies which found that the carbon footprint of landfill biogas ranges from 0.102 to 0.595 t CO₂ eq./t MSW. The variation in the results is due to many factors, including different composition of the waste and the assumptions on venting, recovery and utilisation of biogas for energy. For example, Cherubini et al. (2009) in their study of MSW landfilling in Rome assumed that 25 % of landfill gas escapes to the atmosphere, 25 % is flared and 50 % is utilised for electricity. For these conditions, the carbon footprint was estimated at 0.595 t CO₂ eq./t MSW. Wanichpongpan and Gheewala (2007) also assumed that 25 % of biogas was vented to the atmosphere but that 75 % biogas is collected and utilised for electricity production. The latter is one of the reasons for a much lower carbon footprint than in the other studies (0.102 t CO₂ eq./t MSW). Other reasons include different composition of waste, higher recovery and utilisation rates of biogas and landfill lifetime (20 years compared to 100 years assumed here and in the Ecoinvent (2008) model). Furthermore, although the landfill gas recovery and utilisation rates considered in Ecoinvent (2007) and ILCD (2010) databases are similar to this study, the

composition of waste is different, affecting the amount of biogas generated.

Therefore, these results suggest that, based on the total amount of MSW of 225,000 t/year considered in this study, MSW incineration with energy and metal recovery could save 105,525 tonnes of CO₂ eq. per year compared to incineration without energy and ferrous metals recovery [see Fig. 6: $(-0.179-0.290)$ t CO₂ eq./t MSW \times 225,000 t MSW/year]. Landfilling with energy recovery by comparison saves only 6,300 tonnes of CO₂ eq./year compared to landfilling without energy recovery [$(0.423-0.395)$ t CO₂ eq./t MSW \times 225,000 t MSW/year]. A comparison of the two systems both recovering energy reveals that incineration saves 129,150 t CO₂ eq./year over the landfill biogas [$(-0.179-0.395)$ t CO₂ eq./t MSW \times 225,000 t MSW/year].

Taking this analysis to the UK level and assuming that all of the 14.6 million tonnes of MSW currently landfilled (Defra 2011; DOENI 2011; SEPA 2011; Welsh Government 2011) is incinerated to co-generate heat and electricity, with both systems credited for their outputs as assumed here, would save around 8.38 million tonnes of CO₂ eq. per year [$(-0.179-0.395)$ t CO₂ eq./t MSW \times 14.6 million t MSW/year]. This represents around 1.5 % of the total UK CO₂ eq. emissions of 549.3 million tonnes in 2011 (DECC 2012). By contrast, continuing with the same practice as currently, i.e. landfilling the same amount of waste with biogas recovery as opposed to without the recovery, saves around 408,800 tonnes of CO₂ eq. per year [$(0.423-0.395)$ t CO₂

Fig. 5 Carbon credits for the incineration system for avoided GHG emissions [credits for 1,550 MJ of electricity (0.1858 kg CO₂ eq./MJ), 1,740 MJ of heat (0.0608 kg CO₂ eq./MJ) and 23 kg of ferrous metals (3.243 kg CO₂ eq./kg) per tonne of waste]

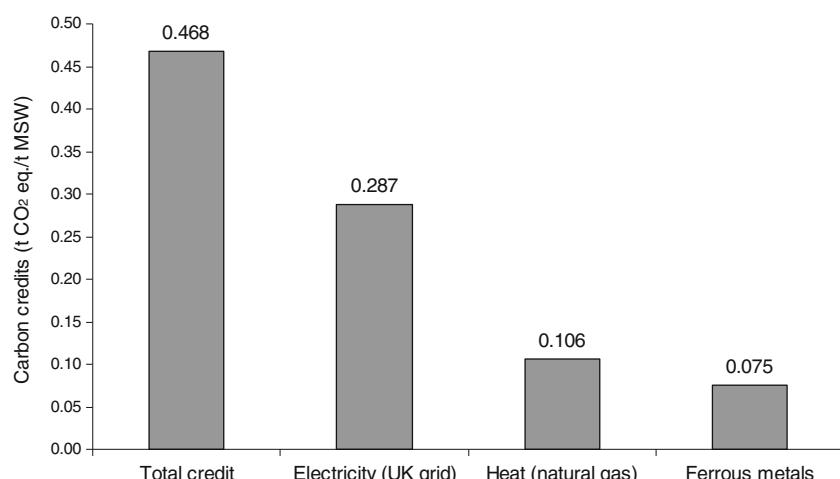
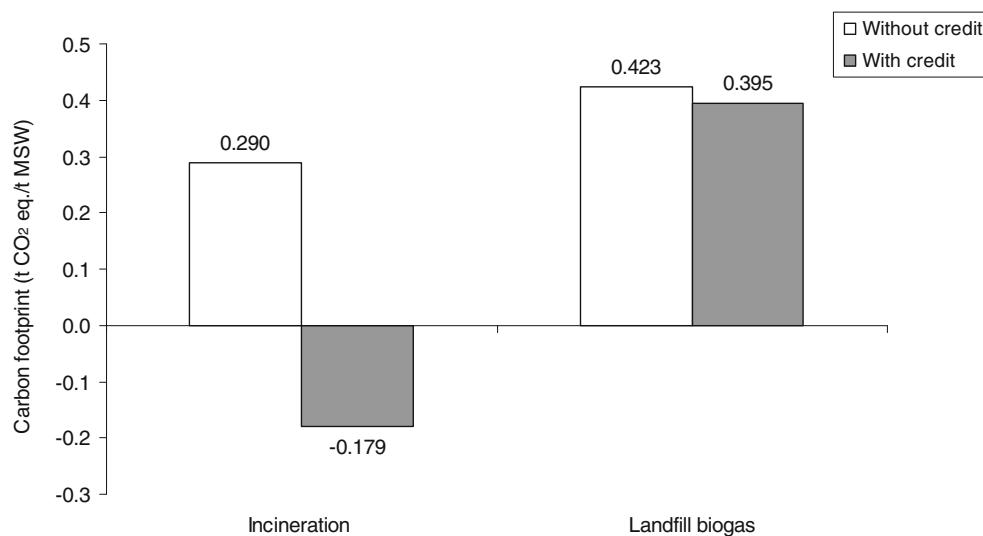


Fig. 6 Total carbon footprint of waste incineration and landfilling (with and without credits)



eq./t MSW × 14.6 million t MSW/year] or 0.07 % of the total UK emissions.

3.2 Hotspot analysis

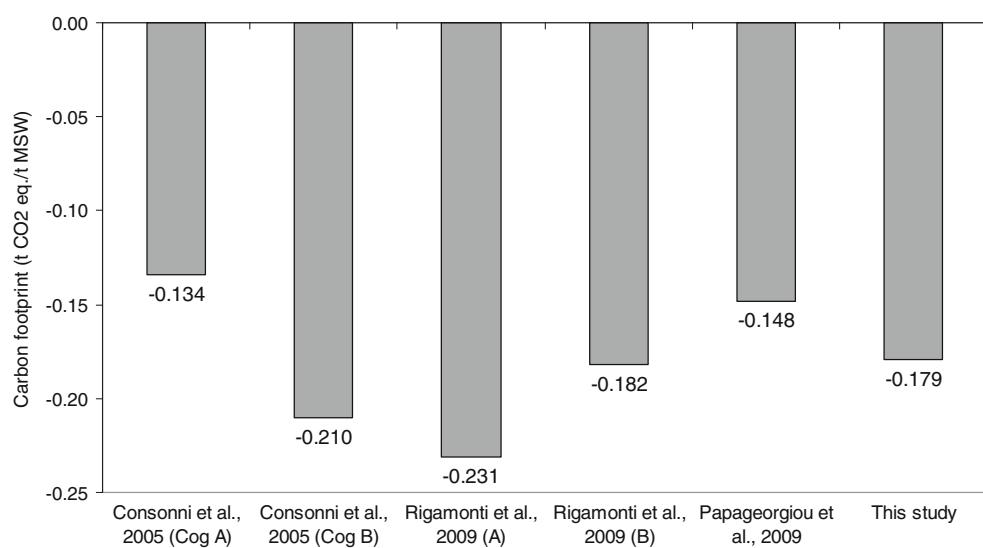
A hotspot analysis has been carried out to identify the main sources of GHG emissions from the two systems. The results in Fig. 9 indicate that stack emissions contribute most to the carbon footprint of the incinerator system (0.227 t CO₂ eq./t MSW). This is due to the emissions of fossil-derived CO₂ from the combustion of waste. Therefore, reducing fossil carbon in the waste would help to improve the carbon footprint of the incinerator; however, this may also affect the calorific value of the waste (e.g. due to a reduced amount of plastics) and consequently the amount of energy that can be recovered.

For the landfill system, the results of the hotspot analysis in Fig. 10 indicate that biogas that is vented to the atmosphere contributes to about 95 % of the total carbon footprint from this system. Thus, increasing the capture rate of the biogas is an important parameter for reducing the carbon footprint from this system.

3.3 Sensitivity analysis

As indicated in the hotspot analysis, the results are influenced by several parameters. For incineration, this includes waste composition and, in particular, the amount of fossil carbon in the waste. The choice of energy credit option can also affect the results. For the landfill system, the carbon footprint depends on the recovery rate of biogas and the rate of its utilisation for energy. Therefore, these parameters have been varied within the sensitivity analysis. A further analysis

Fig. 7 Comparison of the results with other studies of CHP incinerators [Consonni et al. (2005): Cog A, 699 kWh_{el}/t MSW and 2,287 MJ_{th}/t MSW; Cog B, 587 kWh_{el} and 4,574 MJ_{th}; both 600 kt/year MSW; Rigamonti et al. (2009): A, large-scale incinerator (1.2 million people); B, small-scale incinerator (200,000 people); both “scenario 35 %”]



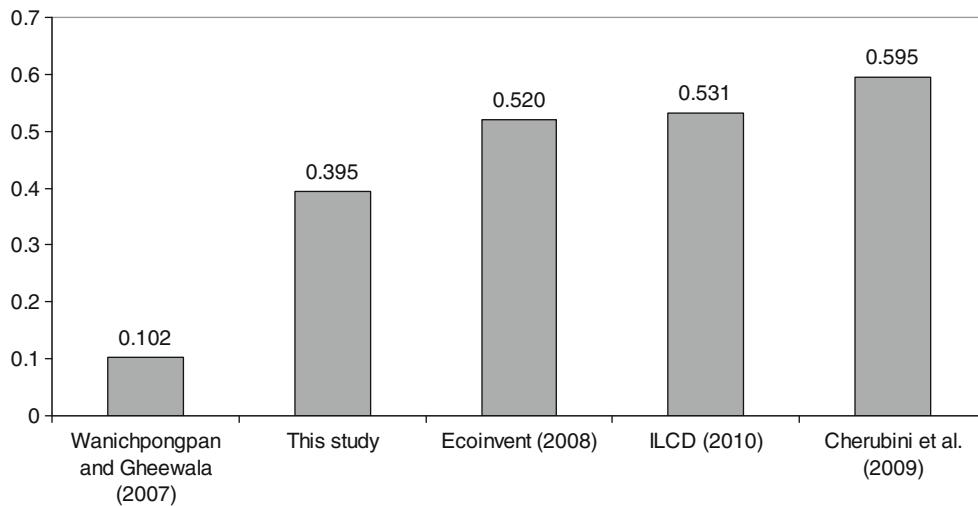


Fig. 8 Comparison of the results with other studies of landfill biogas [Wanichpongpan and Gheewala (2007): Thailand MSW, 75 % biogas collected and utilised for electricity; this study: UK MSW, 35 % of biogas utilised for electricity and heat, 18 % flared, 47 % vented; Ecoinvent (2008): Swiss MSW, 35 % of biogas utilised for electricity

and heat, 18 % flared, 47 % vented; ILCD (2010): 22 % of landfill gas flared, 28 % used for electricity, 50 % vented; Cherubini et al. (2009): Italian MSW, 50 % of biogas utilised for electricity, 25 % flared, 25 % vented]

has also been carried out for the biogas system assuming generation of electricity alone rather than the co-generation as the former is the prevalent practice in the UK (EA 2004).

3.3.1 Waste composition

The amount of fossil carbon in the waste has been varied by assuming different recycling rates of paper (to increase the amount of fossil carbon by decreasing the biogenic carbon). For example, increasing the recycling rates of paper from 40 to 80 % compared to the originally assumed waste

composition given in Table 3 increases the carbon footprint of incineration from 9 to 20 %. This is mainly due to the higher contribution of plastics in waste, which increases from 7 to 8.5 % over the paper recycling range considered, generating higher stack CO₂ emissions (estimated using Eq. 1 for different plastic content in the waste). These trends are illustrated in Fig. 11, showing both the stack emissions and total life cycle carbon footprint of incineration (with energy credits) for different paper recycling rates. It should be noted that changing the amount of paper as well as plastics in the waste would change the calorific value of the waste and therefore

Fig. 9 Hotspot analysis for the incineration system (with credits for energy and metals recovery)

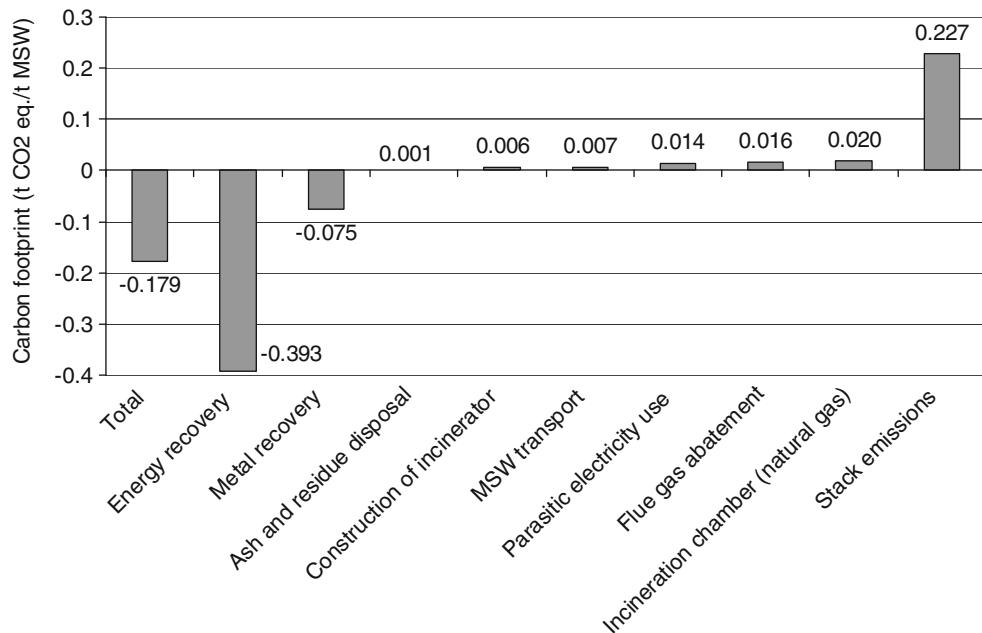
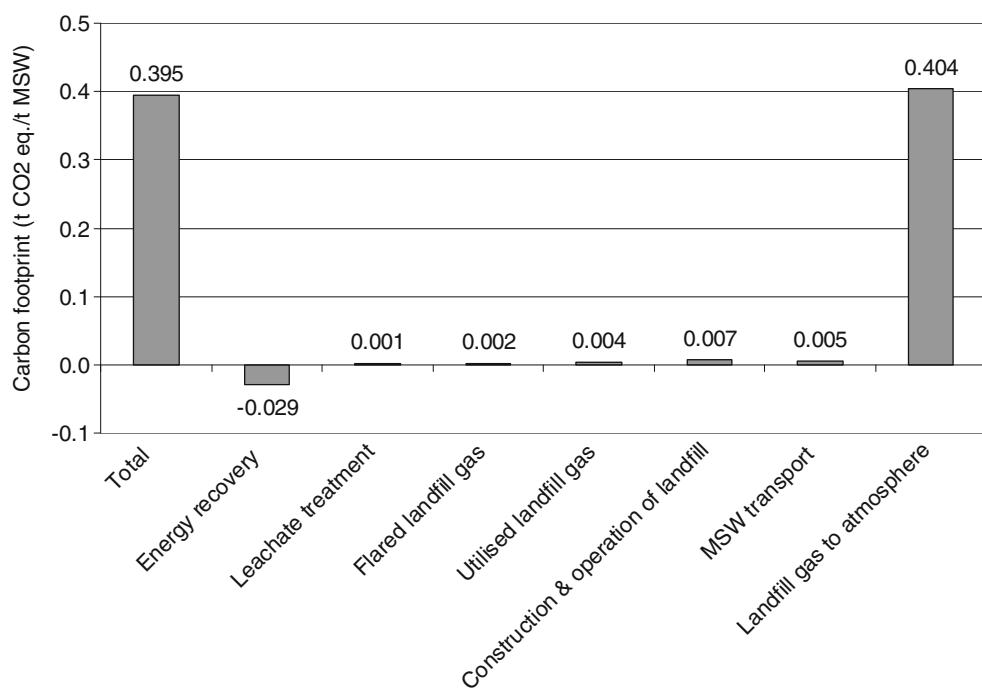


Fig. 10 Hotspot analysis for the landfill system (with credits for energy recovery)



affect the amount of energy recovered. These effects are not considered here due to a lack of data. However, the impact would probably not be significant: although the percentage of paper taken out of the waste is proportionally larger than the increase of plastics, the calorific value of the latter is much higher than the former (typically 40–43 MJ/kg compared to 13–15 MJ/kg).

3.3.2 Energy credits

The impact of the credits for energy recovery from incineration on the overall results is illustrated in Fig. 12. As can be seen, the greatest savings in the GHG emissions from

incineration are achieved when the system is credited for displacing electricity from heavy fuel oil: in that case, the carbon footprint is equal to -0.506 t CO₂ eq./t MSW, compared to -0.179 t CO₂ eq./t MSW when the system is credited for the UK electricity mix. Crediting the system for displacing coal gives the total carbon footprint of -0.346 t CO₂ eq./t MSW. On the other hand, assuming the location of the incinerator in a different country—e.g. Germany or Italy and crediting the system with the corresponding electricity mix, does not influence the results significantly compared to the UK grid (see Fig. 12). If, however, the incinerator is situated in a country with a low-carbon electricity mix such as France, the overall credits would be lower, leading to a

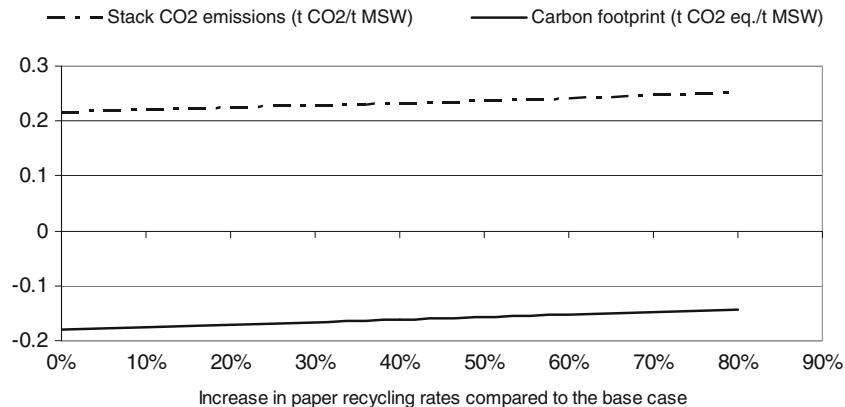


Fig. 11 Influence of waste composition (content of biogenic and fossil carbon) on the carbon footprint of incineration [The results show the increase in paper recycling compared to the waste composition shown in Table 3. The contribution of all other fractions in the waste is increased proportionally to the amount of paper taken out of the waste

for recycling. The proportion of plastics in the waste increases from 7 to 8.5 % for the paper recycling rates considered. The carbon footprint values are with the credits for energy recovery (assuming the same energy recovery rates as for the original composition of the waste.)]

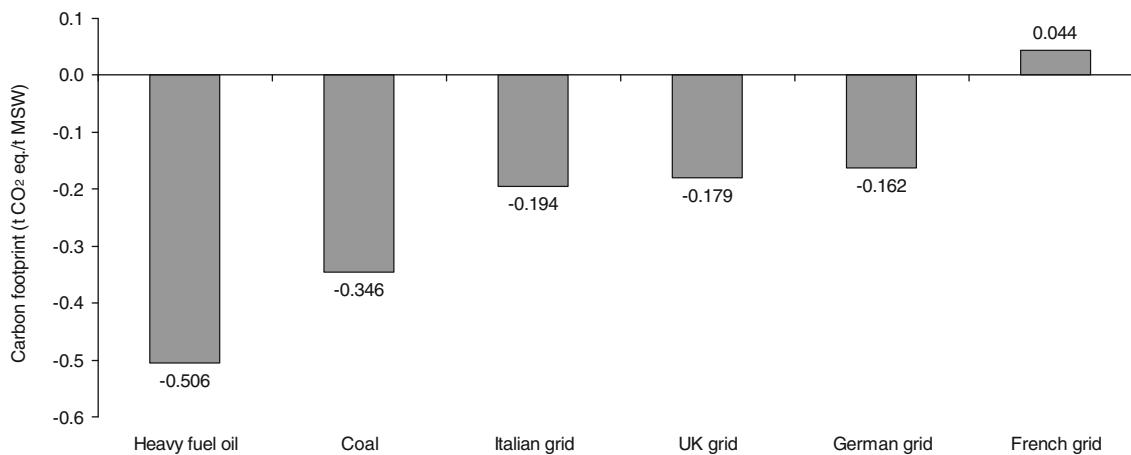


Fig. 12 Influence of different credit options for electricity on the carbon footprint of incineration

higher overall carbon footprint (0.044 t CO₂ eq./t; see Fig. 12) but nevertheless still significantly lower than the carbon footprint of biogas (0.395 t CO₂ eq./t).

3.3.3 Landfill gas recovery rate and its utilisation

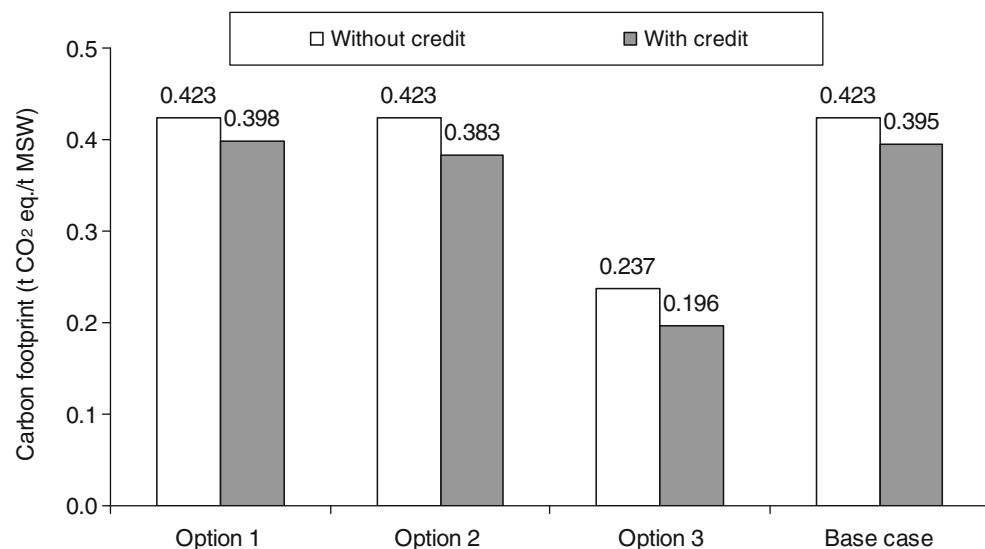
The following three options are considered for the landfill system to examine the impact on the carbon footprint of the gas recovery rate and its utilisation for energy:

- Option 1: Landfill gas is used for electricity generation only. At 28 % efficiency of electricity generation, 133 MJ of electricity is produced per tonne of MSW from the landfill gas.
- Option 2: It is assumed that CHP plant has an overall efficiency of 80 % (heat production is increased to 0.525 MJ/MJ of input and electricity production is kept the same as in the base case, i.e. 0.278 MJ/MJ). As a result, the utilised biogas generates 133 MJ of electricity and 250 MJ of heat/t MSW.

Fig. 13 Influence on the carbon footprint of landfill gas recovery and utilisation for energy [Option 1: landfill gas is used for electricity generation only, at 28 % efficiency; Option 2: landfill gas is used in a CHP plant with heat production of 0.525 MJ/MJ of input and electricity production of 0.278 MJ/MJ; Option 3: 50 % of landfill gas is utilised for electricity and heat production, 25 % is flared and the remaining 25 % is vented to the atmosphere]

- Option 3: It is assumed that 50 % of landfill gas (682 MJ/t MSW) is utilised for electricity and heat production, 25 % is flared and the remaining 25 % is emitted to the atmosphere (Cherubini et al. 2009). Using the same electricity-to-heat production ratio as in the base case (see Section 2.1.2), the utilised landfill gas would produce 189 MJ of electricity and 92 MJ of heat per tonne of MSW.

The results shown in Fig. 13 indicate that the carbon footprint for the landfill system for options 1 and 2 is not significantly different from the base-case results. However, for option 3, the carbon footprint is much lower than for the base case: 0.237 t CO₂ eq./t MSW compared to 0.423 t and 0.196 t vs 0.395 t, before and after crediting for the electricity, respectively. This suggests that increasing the landfill gas recovery and utilisation could significantly lower the carbon footprint of landfilling. However, in comparison to the carbon footprint of incineration, the carbon footprint of the landfill system is still significantly higher (0.196 vs -0.179 t CO₂ eq./t MSW).



4 Conclusions

This paper has examined the carbon footprint of MSW incineration with co-generation of heat and electricity in comparison to waste landfilling with biogas recovery. The results indicate that, for the conditions considered in this study, incineration offers significant savings of GHG compared to disposal by landfill: the total carbon footprint of incineration is $-0.179 \text{ t CO}_2 \text{ eq./t MSW}$, while that from landfilling is $0.395 \text{ t CO}_2 \text{ eq./t MSW}$, with both systems being credited for their respective energy and material outputs. Based on the total amount of MSW of 225,000 t/year considered here, MSW incineration could save around 129 ktonnes of $\text{CO}_2 \text{ eq.}$ per year compared to landfilling with biogas recovery, with both systems co-generating heat and electricity. At the UK level, diverting all the MSW currently landfilled to incineration with energy recovery would save around 8.38 million tonnes of $\text{CO}_2 \text{ eq.}$ per year or 1.5 % of the total UK emissions.

Increasing the amount of fossil carbon in the waste by increasing paper recycling between 40 and 80 % increases the carbon footprint of incineration by 9–20 %. By increasing the landfill gas recovery from 53 to 75 % and utilisation for energy from 35 to 50 %, the carbon footprint of landfill can be reduced by about a half. However, incineration still remains a better option than landfilling under all the conditions considered in this study. The carbon footprint of incineration improves further if instead of the UK energy mix, heavy fuel oil or coal is assumed to be displaced by incineration: it goes down from $-0.179 \text{ t CO}_2 \text{ eq./t MSW}$ to -0.506 and $-0.346 \text{ t CO}_2 \text{ eq./t MSW}$, respectively.

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